

# Using Radio Occultation Data for Ionospheric Studies

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## LONG-TERM GOAL

The long-term goal of this research is to develop Global Positioning System (GPS) radio occultation (RO) techniques that improve our understanding of the Earth's ionosphere and its variability. In the future, RO data promise to become a significant ionospheric data source and will assist in the development of better physics based models, help specify global ionospheric electron density and scintillation fields, provide improved climatology, and also help calibrate other ionospheric sensors and algorithms.

## OBJECTIVES

Our first objective was to modify the radio holographic back propagation (BP) method, which had been previously used, for the localization of electron density irregularities along the line of sight, by taking into account the structure of the irregularities. The modified method has been tested and validated by processing the GPS/MET RO data. The second objective was to include the ionospheric retrieval algorithms for RO data in the COSMIC Data Analysis and Archive Center (CDAAC) software. CDAAC shall analyze data from current and future occultation missions and provide those data and results to the science community.

## APPROACH

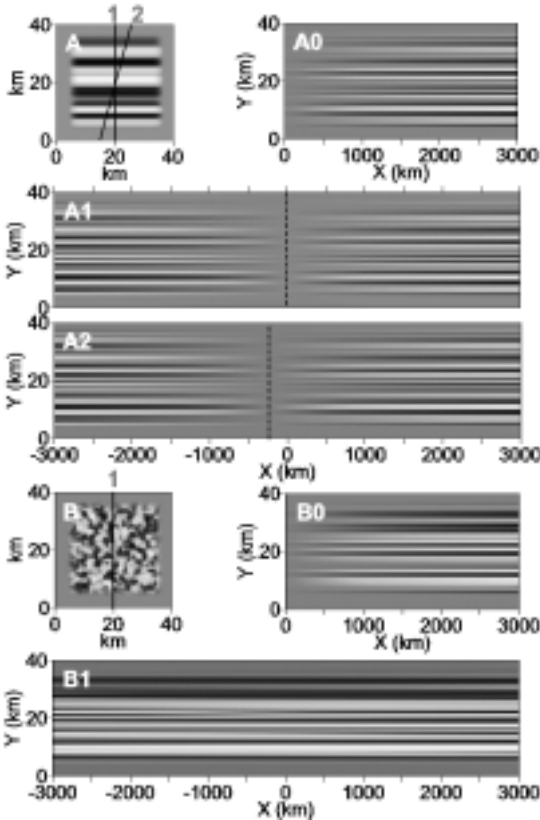
Our previous results (Rocken et al., FY 2000 Annual Report) in localizing electron density irregularities along the line of sight had been obtained by use of 2-dimensional (2D) BP. The BP was based on the ad hoc assumption of homogeneity of the refractivity irregularities and thus of the scattered electromagnetic (EM) waves in the transverse direction to the BP plane. This assumption has been implicitly used in the literature for localizing ionospheric irregularities [Schmidt and Tauriainen, 1975; Sokolovskiy, 2000; Gorbunov et al., 2001]. Our more detailed numerical simulations that we performed during this year show that this assumption and failing to account for the structure of the irregularities may result in significant errors of the localization.

Fig.1 shows the results of our numerical simulations. Fig.1A shows a 1D equivalent phase screen, which models the effect of the ionospheric irregularities. Fig.1 A0 shows the amplitude of the EM waves propagated through the screen, positioned at  $X=0$ , in cross section 1 (as indicated in Fig.1A). Fig.1A1 shows the amplitude of the EM field obtained by 2D BP in cross section 1. As seen, in this case the position of the phase screen can be determined based on minimum of amplitude modulation, indicated by a dashed line in the Figure. Fig.1A2 shows the amplitude of the EM field after BP in cross

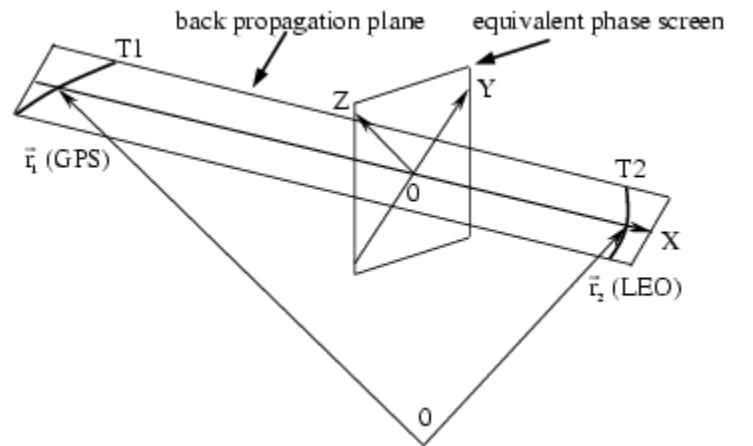
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14. ABSTRACT <b>The long-term goal of this research is to develop Global Positioning System (GPS) radio occultation (RO) techniques that improve our understanding of the Earth's ionosphere and its variability. In the future, RO data promise to become a significant ionospheric data source and will assist in the development of better physics based models, help specify global ionospheric electron density and scintillation fields, provide improved climatology, and also help calibrate other ionospheric sensors and algorithms.</b>					
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section 2 (as indicated in Fig.1A) inclined by 15 deg. Relative to cross section 1, again, by assuming homogeneity of the EM field in the direction transverse to 2. As seen, the position of the phase screen is determined based on the minimum of amplitude modulation with an error of 200-300 km. Fig.1B shows the 2D equivalent phase screen. Fig.1B0 shows the amplitude of EM waves propagated through the screen, positioned at  $X=0$ , in cross section 1 (as indicated in Fig.1B). Fig.1B1 shows the amplitude of the EM field obtained by 2D BP in cross section 1. As seen, in the case of isotropic refractivity irregularities modeled by the phase screen B the position of the equivalent phase screen may not be determined based on finding the minimum of amplitude modulation after 2D BP. The reason for this is the focussing and defocusing in the direction transverse to 1 affects the 3D EM field B1, but was not taken into account when calculating the EM field by 2D BP.

Ionospheric irregularities are normally anisotropic, they are aligned along magnetic field lines, and the aspect ratio of their scales is  $\gg 1$ . Thus the BP plane has to be chosen orthogonal to the projection of the vector of the magnetic field  $\mathbf{B}$  on the equivalent phase screen. Since the direction of  $\mathbf{B}$  in the Earth's magnetosphere is known with an accuracy of 10-15 deg one can expect to achieve localization of the irregularities along the line of sight with an accuracy of about 200 km. We developed new software, which determines the BP plane for each position of the equivalent phase screen on the line of sight to be normal to the projection of  $\mathbf{B}$  on the screen. This is shown in Fig.2 where the Z-axis coincides with the vector  $\mathbf{B}$ . Then the trajectories of the GPS and LEO are projected onto the BP plane (T1 and T2 in Fig.2). Since for the BP (numerical solution of Helmholtz equation in a vacuum for a given boundary conditions, described in last year's report) a transmitter must be stationary, the Y coordinate of the LEO satellite is corrected at each time to account for the shift of the Y coordinate of the GPS with respect to its median value  $Y=0$ , i.e.,  $\Delta Y_2 = Y_1 X_2 / X_1$ . Then the BP is performed as for the stationary GPS at  $Y=0$ .



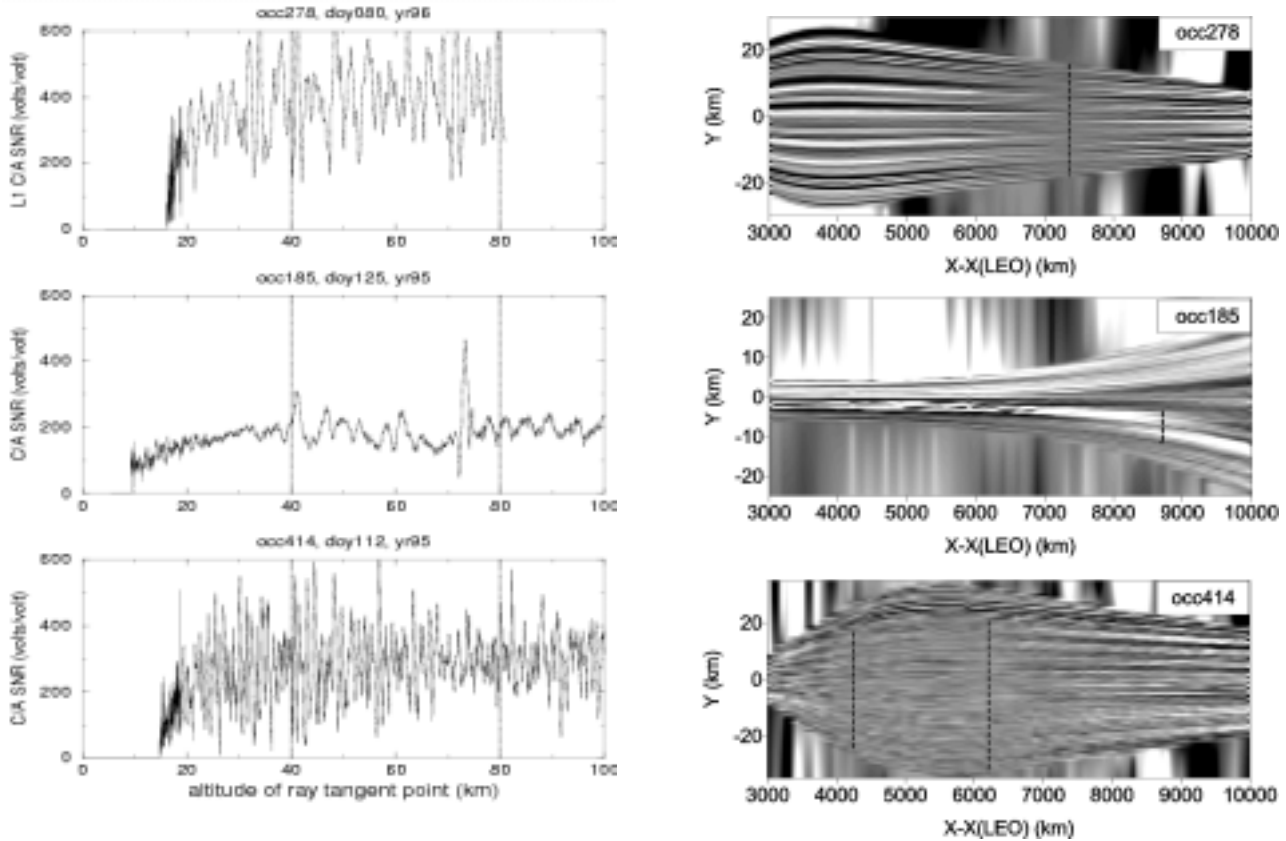
*Figure 1 (left) shows the results of numerical simulations as explained in the text of the paper.*



*Figure 2 (right) shows the geometry of the equivalent phase screen and the BP plane.*

## WORK COMPLETED

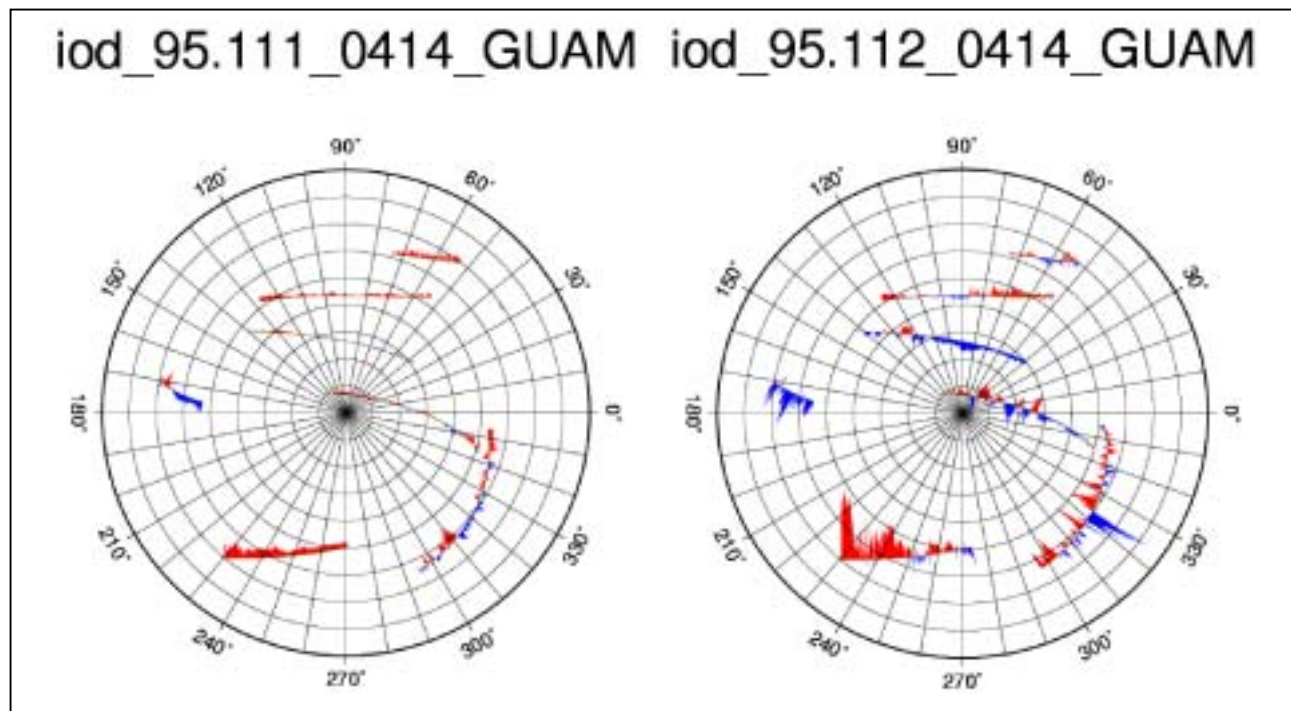
We implemented the modified radio holographic (BP) method, which accounts for the direction of the magnetic field along the line of sight and tested it on high rate (50 Hz) GPS/MET data. Example results are shown in Figs.3 and 4. Fig.3 shows L1 SNR as a function of the altitude of the ray tangent point for three occultations. Fig.4 shows the amplitude of the BP EM field as the function of the distance from LEO ( $X=3000$  km approximately corresponds to the tangent point of the beam) for those same occultations. Complicated shapes of the amplitude patterns are due to the fact that for each  $X$  the orientation of the BP plane is different according to the projection of  $B$  on the plane normal to the line of sight at that  $X$ . Correspondingly the projections of the GPS and LEO orbits on the BP plane (T1 and T2 in Fig.2) are different and thus the difference in the cross section of the beam. For occ.278 there is a clear minimum of the cross beam amplitude modulation at a distance of about 7300 km from LEO which corresponds to the altitude of the electron density irregularities of about 1300 km (25.5N, 155.5W, 10:03 UTC). For occ.185 the BP amplitude indicates a strong irregularity at a distance of about 8700 km from LEO which corresponds to the altitude of about 2200 km (54.5N, 105.5E, 06:32 UTC). For occ.414 there are two minima of the cross beam amplitude at distances of about 4200 and 6200 km from LEO. The right minimum corresponds to the altitude of about 800 km (15N, 152E,



*Figure 3 (left) shows the SNR for three GPS/MET occultations as a function of the ray tangent altitude. Vertical dashed lines show the sections of the RO signal that were used for BP. Figure 4 (right) shows the corresponding BP amplitude modulation. A dashed line at the location of minimum modulation marks the distance of the irregularity from the LEO.*

14:14 UTC). We observe two minima in a number of occultations. At present we can not conclude whether they are caused by irregularities located at two different regions. It is possible that one of the minima is caused by a different orientation of the vector B along the line of sight (as illustrated in the simulations in Fig.1) and thus is false, i.e. it does not correspond to any irregularities. A possible way to verify this would be to apply BP in a number of planes, each corresponding to a different orientation of the vector B. Then it would be possible to estimate the location of the irregularities through the position of the minimum of the cross beam amplitude modulation X in that plane which is normal to the projection of the vector B on the equivalent phase screen at that X. This will require running BP a number of times for each occultation which is very CPU time consuming and it is not feasible with our present code. For this purpose we plan to substantially modify our BP code.

We have started the process of validating the irregularity location technique with correlative ionosonde and ground GPS data. The qualitative and descriptive codes in the National Geophysical Data Center (NGDC) ionosonde data can be used to determine when an ionosonde is experiencing spread echoes (spread F), a phenomenon caused by ionospheric irregularities. GPS ground data, sampled at many sites around the world at 30 seconds, can also be used to locate regions with ionospheric irregularities by examining the rate of change of Total Electron Content (ROT) along the ray path to each satellite. GPS/MET occultation data from 95.106-96.302 have been analyzed in an attempt to localize regions that contain ionospheric irregularities. For this period, 55 occultations contained well-determined minima in the amplitude perturbation of the back-propagated electromagnetic field. Unfortunately, none of the 55 localized regions occurred close to an ionosonde site, due to the lack of ionosonde stations near the equator. However, a few of the 55 localized regions occurred sufficiently close to a GPS station to provide some validation. GPS/MET occultation #0414 on 1995.112 showed evidence of irregularities near a latitude/longitude/height point of 15deg/152deg/800km, which is close to GUAM. Figure 5 shows azimuth/elevation sky plots of ROT for the IGS site GUAM on consecutive days, 1995.111 and 1995.112, for a 2-hour interval surrounding the occultation event. The latitude/longitude/height point of the GPS/MET sensed irregularity region corresponds to an azimuth of ~80 degrees and an elevation of ~46 degrees (X marks the spot in the right panel) as viewed from GUAM, which lies on one of the GPS satellite paths. The figure shows that the ionosphere is disturbed on 1995.112 as compared to 1995.111, which is encouraging, but is not a definitive validation. Note the change in ROT magnitude at the midpoint of the satellite path below the X. This could correspond to the GPS satellite entering/exiting the well-defined irregularity region that is sensed with GPS/MET. More data must be processed to provide a more definitive validation of this technique.



**Figure 5** Sky (Az/El, 0 = North, center of the bulls-eye is zenith from the station GUAM) maps of the rate of change of TEC for IGS GPS site GUAM illustrating ionospheric irregularity activity for consecutive days 1995.111 and 1995.112. Data from GPS/MET occultation #0414 on 1995.112 showed an irregularity region at azimuth ~80 deg and elevation ~46 deg (see X in right panel).-

Finally, we have included ionospheric profiling processing, using the Abel transform, in the CDAAC software. Electron density profiles are now retrieved by the CDAAC and the results are stored in a web-accessible database. This new functionality of the CDAAC is still tested but we plan to provide ionospheric occultation data from GPS/MET and other satellite missions via the CDAAC shortly.

## IMPACT/APPLICATION

An automated procedure to localize ionospheric irregularities on RO links, could be used in near real time to define regions that cause radio communication problems.

## TRANSITIONS

We have been collaborating with the Multidisciplinary Research Program of the University Research Initiative (MURI) supported Global Assimilation of Ionospheric Measurements (GAIM) program and will continue to provide GPS RO data and analysis expertise to support this MURI effort.

## RELATED PROJECTS

Below we list several projects that work on using GPS occultation data. We are providing all of these groups with data and work closely with most of them.

(1) The Danish Meteorological Institute and Saab Ericsson of Sweden are working on the development of software for ionospheric data retrieval in response to a NASA/NOAA/USAF Integrated Program Office (IPO) contract.

(2) Lung-Chih Tsai and Ming-Quey Chen at the National Central University in Taiwan are comparing GPS/MET profile data to digisonde data and are assisting with TIE-GCM simulations, respectively.

## **REFERENCES**

Gorbunov, M.E., A.S. Gurvich, and A.V. Shmakov, Back propagation and radio-holographic methods for investigation of sporadic ionospheric E-layers from Microlab-1 data. *Int. J. of Remote Sensing*, 2001, in press.

Schmidt, G, and A. Tauriainen, The localization of ionospheric irregularities by the holographic method, *JGR*, 80(31),4313-4324, 1975.

Sokolovskiy, S. V., Inversions of radio occultation amplitude data, *Radio Science*, 35(1), 97-105, 2000.